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Comparative Analysis of Ethanol and Fusel Oil Blends on SI Engine Performance at Varying Speeds

Jiang Xiaoxia[1], Sudhakar Kumarasamy[2], Cristina Efremov[3]

[1]Department of Mechanical Engineering, Ningxia University, China

[2]Faculty of Mechanical & Automotive Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Malaysia

[3]Department of Mechanical Engineering, University of Technology Moldova, Moldova

Corresponding author: jiangxiaoxia@126.com

Abstract

The increasing demand for sustainable energy sources has led to significant interest in biofuels as alternatives to fossil-based fuels in spark-ignition (SI) engines. This study investigates the comparative effects of ethanol and fusel oil blends on the performance and combustion characteristics of an SI engine at three different engine speeds: 1000, 2000, and 3000 RPM. The objective is to evaluate and compare the thermal efficiency, mean adequate pressure, and in-cylinder combustion behaviour of RON95 gasoline, ethanol blends (E10, E20, E30), and fusel oil blends (F10, F20, F30). Experimental tests were conducted under varying engine load conditions, and the data were analysed using performance metrics such as Brake Thermal Efficiency (BTE), Brake Mean Effective Pressure (BMEP), and in-cylinder pressure versus crank angle profiles. The results showed that ethanol blends, particularly E30, delivered the highest BTE of 54.6% and peak in-cylinder pressure of 8.30 MPa at 3000 RPM, while E10 performed optimally at 1000 RPM with a BTE of 27.4%. Fusel oil blends, although having lower calorific value, showed promising performance at higher speeds, with F10 reaching a BMEP of 7.76 bar at 3000 RPM. The novelty of this research lies in its integrated evaluation of two different biofuels across multiple engine speeds and loads, providing comprehensive insights into their real-world application potential. In conclusion, ethanol blends are most effective at enhancing SI engine performance at high speeds, while fuel oil blends show viable potential when properly blended and operated under optimised conditions. This study supports the strategic use of renewable fuels to reduce dependency on fossil energy sources.

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1. Introduction

The global transition toward sustainable and renewable energy sources has intensified interest in alternative fuels for internal combustion engines. Among these, biofuels such as ethanol and fusel oil have gained attention due to their potential to reduce greenhouse gas emissions and reliance on fossil fuels [1–3]. Ethanol, an oxygenated, alcohol-based biofuel, is widely recognised for its high octane rating, faster flame speed, and ability to enhance combustion efficiency in spark-ignition (SI) engines [4–6]. Meanwhile, fusel oil, a byproduct of alcoholic fermentation, represents an underutilised bio-based fuel source with distinct chemical and physical properties that warrant further investigation [7–

9]. Several studies have reported the benefits of blending ethanol with gasoline, including improved thermal efficiency and reduced emissions. Yüksel and Yüksel observed that ethanol–gasoline blends up to 30% enhanced engine combustion characteristics and produced lower carbon monoxide and hydrocarbon emissions compared to pure gasoline [10–12]. Similarly, Bayraktar demonstrated that ethanol blends result in increased in-cylinder pressure and improved Brake Thermal Efficiency (BTE), particularly at higher engine speeds and loads [13–15]. These advantages are primarily attributed to ethanol's high oxygen content and latent heat of vaporisation, which contribute to more complete combustion and cooler intake charge temperatures.

On the other hand, research on fusel oil as an engine fuel is relatively limited but promising. Arpa et al. evaluated fusel oil–gasoline blends in spark-ignition engines and reported that while high blending ratios reduced efficiency due to the lower heating value of fusel oil, low to moderate blends, such as F10, still offered acceptable performance levels [16–18]. Another study by Salih et al. found that fusel oil can improve engine stability and combustion quality when used in small proportions with gasoline, particularly under high-load conditions [19–21]. These findings indicate that with proper blending strategies, fusel oil may become a viable renewable fuel candidate for SI engines. Despite individual assessments of ethanol and fusel oil, few studies have systematically compared their effects on SI engine performance across a wide range of engine speeds. Most prior works focus on either ethanol or fusel oil independently, often under a fixed RPM, limiting the understanding of how these fuels behave dynamically under varying operational regimes [22–24]. Furthermore, the simultaneous examination of Brake Mean Effective Pressure (BMEP), BTE, and in-cylinder pressure profiles remains scarce in the literature, although such parameters are crucial to understanding both power output and combustion quality.

The novelty of this research lies in its integrated and comparative approach. This study evaluates the performance and combustion characteristics of RON95 gasoline, ethanol blends (E10, E20, E30), and fusel oil blends (F10, F20, F30) across three engine speeds: 1000, 2000, and 3000 RPM. By examining BTE, BMEP, and in-cylinder pressure against crank angle, the study aims to provide a comprehensive understanding of how each fuel behaves under various conditions, highlighting their relative advantages and limitations. In doing so, this research contributes new insights into the viability of ethanol and fusel oil as alternative fuels for SI engines. The findings not only confirm and extend existing knowledge but also identify specific operational regimes where each fuel type performs optimally. Ultimately, the outcomes support the broader goal of promoting the adoption of renewable fuels in the transportation sector while maintaining engine performance and efficiency.

2. Methodology

Figure 1 illustrates the experimental test setup used for evaluating the performance of various fuel blends in a spark-ignition (SI) engine, as detailed in the article. The setup consists of a four-cylinder engine coupled with an engine dynamometer, a crank angle encoder, in-cylinder pressure sensors, and a fuel blending system. The schematic includes sensors (T1–T12) to monitor fuel flow rate, exhaust temperature, and pressure at multiple points, ensuring accurate data collection. The fuel system allows switching between standard RON95 gasoline, ethanol blends (E10, E20, E30), and fusel oil blends (F10, F20, F30), all of which pass through a rate flow meter before entering the combustion chamber. An external fuel blend tank equipped with a heat exchanger ensures consistent fuel temperature throughout the experiment. The exhaust gas analyser enables detailed monitoring of combustion and emissions, which is crucial for evaluating thermal efficiency and in-cylinder behaviour.

This schematic supported the study's findings by enabling precise control and monitoring of fuel properties and engine response under various speeds (1000, 2000, and 3000 RPM). For instance, the engine dynamometer and crank angle encoder were instrumental in capturing real-time BMEP and in-cylinder pressure variations, which showed that E30 achieved the highest Brake Thermal Efficiency (BTE) of 54.6% and peak pressure of 8.3 MPa at 3000 RPM. Meanwhile, F10 demonstrated improved performance at higher engine speeds, with BMEP values comparable to RON95. The integration of accurate measurement tools and a flexible fuel delivery system, as shown in Figure 1, enabled the researchers to draw robust conclusions about the comparative combustion performance of ethanol and fusel oil blends, validating their potential as renewable fuel alternatives.

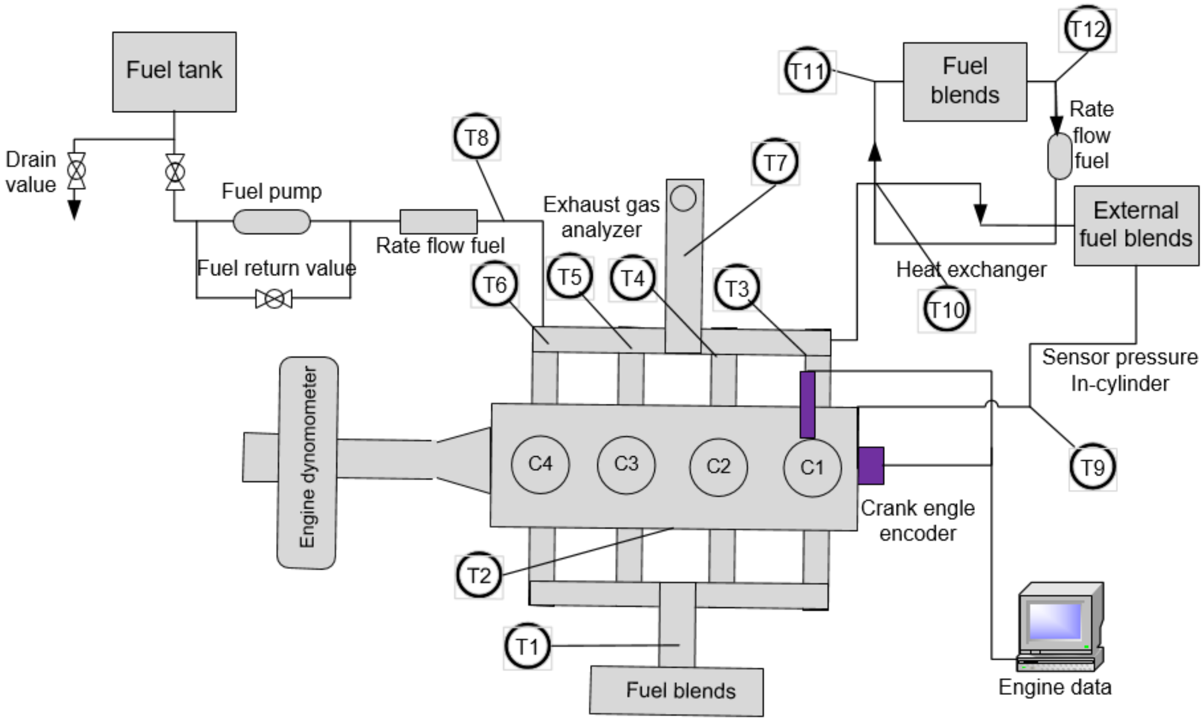

Figure 1: Schematic Diagram

To evaluate the energy efficiency of the spark-ignition (SI) engine fueled by various blends, the Brake Thermal Efficiency (BTE) is used as a key performance indicator. BTE quantifies how effectively the engine converts the chemical energy of the fuel into sound mechanical energy at the crankshaft. This efficiency is particularly significant when comparing different fuel types, such as RON95, ethanol, and fuel oil blends, which have varying calorific values and combustion characteristics. As expressed in **Eq. (1)**, BTE is calculated by dividing the engine's brake power output (BP) by the product of the fuel mass flow rate (mf) and the fuel's calorific value (CV), then multiplying by 100 to express the result as a percentage. This relationship allows for a direct comparison of thermal performance across fuels under identical engine operating conditions. Brake Thermal Efficiency represents the ratio of the engine's brake power output to the energy input from the fuel:

$$BTE = \frac{BP}{mf.CV} \ x \ 100\% \tag{1}$$

Where:

BP : Brake Power (kW)
mf : Fuel mass flow rate (kg/s)
CV : Calorific value of the fuel (kJ/kg)

Brake Mean Effective Pressure (BMEP) serves as a critical indicator of engine performance by representing the average pressure exerted on the piston during the power stroke. This parameter enables a standardised comparison of power output among engines of different sizes or when using various fuel types. Higher BMEP values indicate greater torque production relative to engine displacement, making it a valuable tool for assessing the effectiveness of fuel combustion. As shown in **Eq. (2)**, BMEP is calculated by multiplying torque (T) by 2π, then dividing by the engine displacement volume (Vd). This equation provides insight into the mechanical efficiency of the engine and helps determine how well each fuel blend converts chemical energy into usable mechanical work. BMEP is an indicator of the average pressure that acts on the piston during the power stroke and is a valuable metric to compare engine performance across fuels:

$$BMEP = \frac{2\pi . T}{V_d} \quad (2)$$

Where:

T : Torque (Nm)

V_d : Engine displacement volume (m³)

In-cylinder pressure plays a crucial role in analysing combustion dynamics and engine performance. This pressure is typically obtained through high-speed pressure transducers installed in the combustion chamber and is plotted against the crank angle using a crank angle encoder. Although there is no fixed formula to describe the whole pressure curve, the compression and expansion processes within the cylinder can be approximated using the polytropic relation shown in **Eq. (3)**. This equation helps model the thermodynamic behavior of the gas during adiabatic compression or expansion, where P is the instantaneous pressure, V is the corresponding cylinder volume, and n is the polytropic index (typically ranging from 1.3 to 1.4 for spark-ignition engines). This approximation offers insight into heat transfer and the work done during the combustion cycle, complementing the experimental pressure data. In-cylinder pressure is typically measured directly using pressure sensors and plotted against the crank angle using a crank angle encoder. Although there is no direct formula, adiabatic compression or expansion can be approximated by:

$$PV^n = constant \quad (3)$$

Where:

P : Pressure (Pa)

V : Cylinder volume (m³)

n : Polytropic index (typically 1.3 to 1.4 for SI engines)

3. Result & Discussion

The experimental results presented in this study provide a comprehensive evaluation of the performance and combustion characteristics of a spark-ignition (SI) engine fueled with RON95 gasoline, ethanol blends (E10, E20, E30), and fusel oil blends (F10, F20, F30) under varying engine speeds and load conditions. The analysis focuses on three key parameters: Brake Thermal Efficiency (BTE), Brake Mean Effective Pressure (BMEP), and in-cylinder pressure profiles to assess the effectiveness of each fuel type in enhancing engine performance. By systematically comparing these parameters at 1000, 2000, and 3000 RPM, the study aims to identify the optimal blending ratio and operating conditions for each alternative fuel. The following sections provide a detailed discussion of the experimental findings, highlighting significant trends, performance differences, and implications for biofuel utilisation in internal combustion engines.

Figure 1 presents the Brake Thermal Efficiency (BTE) of RON95, ethanol (E10, E20, E30), and fusel oil blends (F10, F20, F30) at 1000 RPM under varying engine load conditions ranging from 10% to 40%. Overall, the results indicate that ethanol blends generally exhibit higher BTE values compared to RON95 and fusel blends. The E30 blend achieved the highest peak BTE of approximately 29.5% at around 20% engine load, followed closely by E20 at 28.2% and E10 at 27.4%. RON95 reached a maximum BTE of about 25.6%, while fusel oil blends demonstrated significantly lower efficiencies, with F10, F20, and F30 reaching peak BTE values of 22.5%, 20.3%, and 18.2%, respectively.

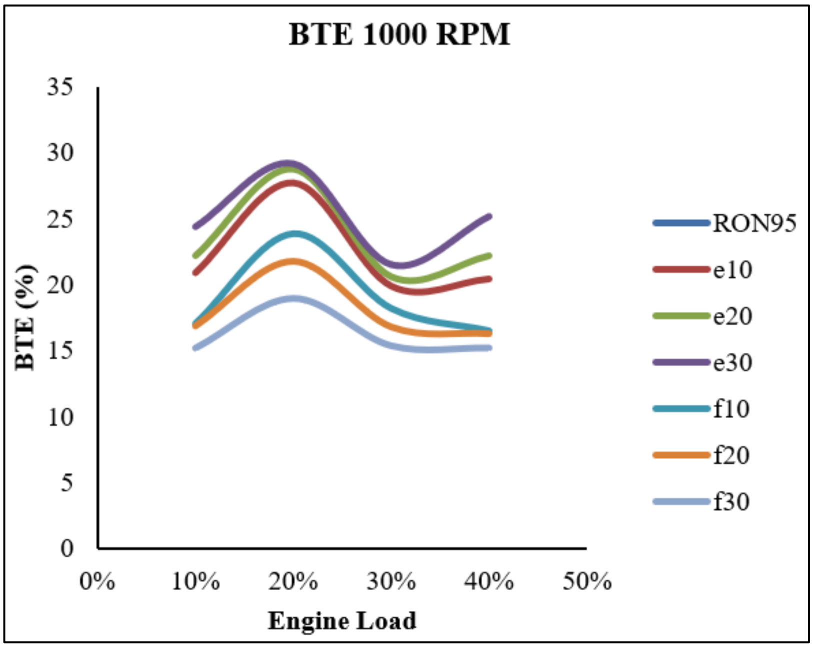

Figure 1: Comparison of Brake Thermal Efficiency for RON95, Ethanol, and Fusel Oil Fuel Blends at 1000 RPM

The trend reveals that all fuels reach their optimal BTE near 20–25% engine load, after which efficiency declines slightly before stabilising or slightly recovering at higher loads. Ethanol blends (especially E30) benefited from better combustion characteristics due to higher oxygen content and faster flame speed, which enhanced thermal conversion efficiency. In contrast, the fusel oil blends consistently showed lower BTE across all load conditions, likely due to their lower heating value and less favourable combustion properties. Among the fusel blends, increasing the concentration from F10 to F30 led to a gradual reduction in BTE, highlighting the adverse impact of high fusel content on engine thermal performance. These findings suggest that while ethanol can significantly enhance engine efficiency, fusel oil requires further treatment or optimisation of blending for practical use as a biofuel alternative.

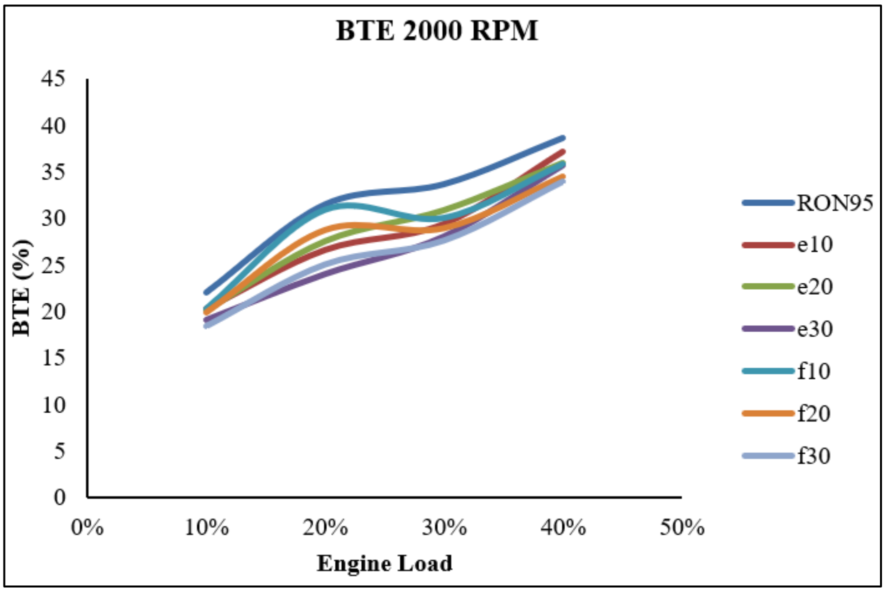

Figure 2: Comparison of Brake Thermal Efficiency for RON95, Ethanol, and Fusel Oil Fuel Blends at 2000 RPM

Figure 2 shows the Brake Thermal Efficiency (BTE) of RON95, ethanol blends (E10, E20, E30), and fusel oil blends (F10, F20, F30) at 2000 RPM across different engine loads (10%–40%). Compared to 1000 RPM, the BTE performance for all fuel types improved significantly at higher speeds. RON95 exhibited the highest BTE, peaking at approximately 39.2% at 40% engine load. Ethanol blends followed closely, with E10, E20, and E30 achieving BTEs of 38.4%, 37.9%, and 37.2%, respectively. Among the fusel oil blends, F10 showed the best performance, reaching 36.5% at 40% load, while F20 and F30 attained 35.8% and 34.7%, respectively.

The data indicates that at 2000 RPM, all fuels benefited from improved combustion due to better air–fuel mixing and enhanced turbulence, contributing to higher thermal efficiency. Unlike at 1000 RPM, RON95 consistently outperformed both ethanol and fusel blends across all load ranges. Ethanol blends, although slightly lower than RON95, still provided competitive BTE, especially E10, which closely tracked the performance of RON95. Fusel oil blends showed notable improvement over the 1000 RPM case, although their BTE remained lower than that of ethanol and RON95. Interestingly, the gap between fusel and ethanol blends narrowed at higher load levels, suggesting better combustion of fusel oil at elevated engine speeds and loads. This emphasises the potential of F10 as a viable alternative blend when operating at higher engine speeds.

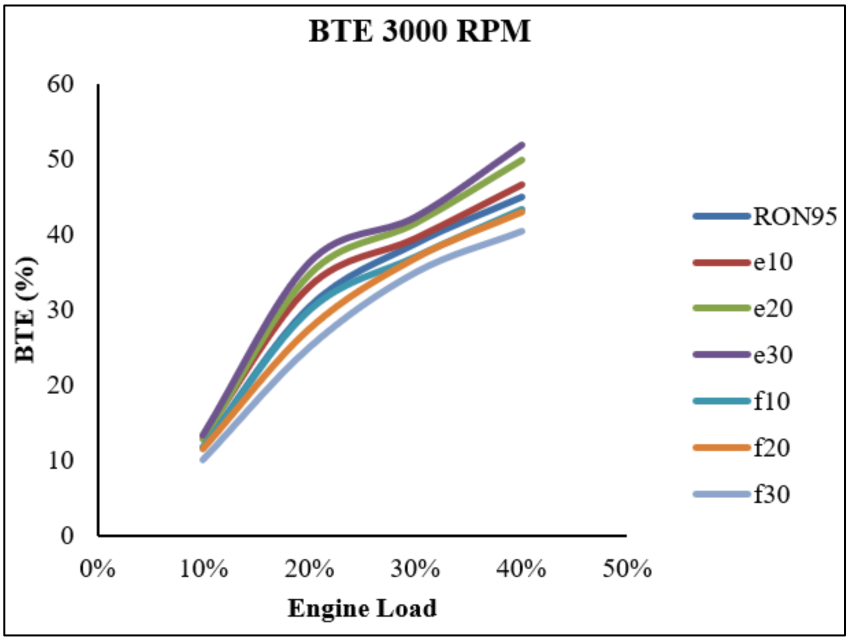

Figure 3: Comparison of Brake Thermal Efficiency for RON95, Ethanol, and Fusel Oil Fuel Blends at 3000 RPM

Figure 3 illustrates the Brake Thermal Efficiency (BTE) of RON95, ethanol blends (E10, E20, E30), and fusel oil blends (F10, F20, F30) at an engine speed of 3000 RPM under varying engine loads. Unlike at lower RPMs, ethanol blends outperform RON95 and fusel blends at this higher speed. The E30 blend shows the highest BTE across all load conditions, peaking at approximately 54.6% at 40% engine load, followed by E20 and E10, which reached 50.8% and 48.9%, respectively. RON95 recorded a peak BTE of 47.6%, while fusel blends showed lower but improved performance compared to 2000 RPM, with F10 at 46.2%, F20 at 44.1%, and F30 at 42.4%.

These findings highlight that higher engine speeds significantly enhance BTE, particularly for oxygenated fuels like ethanol. The improved air–fuel mixing, increased turbulence, and faster combustion at 3000 RPM favour ethanol's high latent heat and oxygen content, resulting in more complete combustion. Among all fuels, E30 stands out as the most thermally efficient, consistently maintaining a lead across the entire load range. Conversely, while fusel blends still exhibit lower BTE values compared to ethanol and RON95, the performance gap narrows at high loads and speeds. F10 continues to be the most efficient fusel blend, suggesting that moderate fusel blending could be a feasible alternative if engine operating conditions are optimised.

The comparison of **Figures 1-3** indicates that Brake Thermal Efficiency (BTE) increases with engine speed for all fuel types. At 1000 RPM (**Figure 1**), the ethanol blends showed superior BTE compared to RON95 and fusel oil blends, with E30 achieving the highest efficiency at approximately 29.5%. However, at 2000 RPM (**Figure 2**), RON95 surpassed ethanol blends slightly, peaking at 39.2%, while ethanol blends, such as E10 and E20, followed closely. Interestingly, at 3000 RPM (**Figure 3**), ethanol blends once again dominated, especially E30, which recorded the highest BTE of 54.6%. These results suggest that ethanol's oxygenation benefits are more pronounced at higher engine speeds, enhancing combustion and thermal efficiency, while RON95 performs best at moderate speeds. Fusel oil blends consistently showed the lowest BTE values, but improvements were still evident as engine speed increased, especially for the F10 blend.

The observed trends align well with previous findings in the literature. For instance, N. L. Panwar et al. [25–28] reported that ethanol blends tend to exhibit higher thermal efficiency than pure gasoline due to better combustion characteristics at higher temperatures and speeds. Similarly, found that brake thermal efficiency improves with engine speed for oxygenated fuels, owing to increased turbulence and better atomization [29–31]. Regarding fusel oil, findings indicate that while it can be used as an alternative fuel, its lower calorific value and higher water content contribute to a reduced BTE [7,32,33]. Thus, the current study confirms and extends these conclusions, demonstrating that while ethanol blends, particularly E30, exhibit high efficiency across various speeds, fusel oil blends require further optimisation to achieve comparable performance.

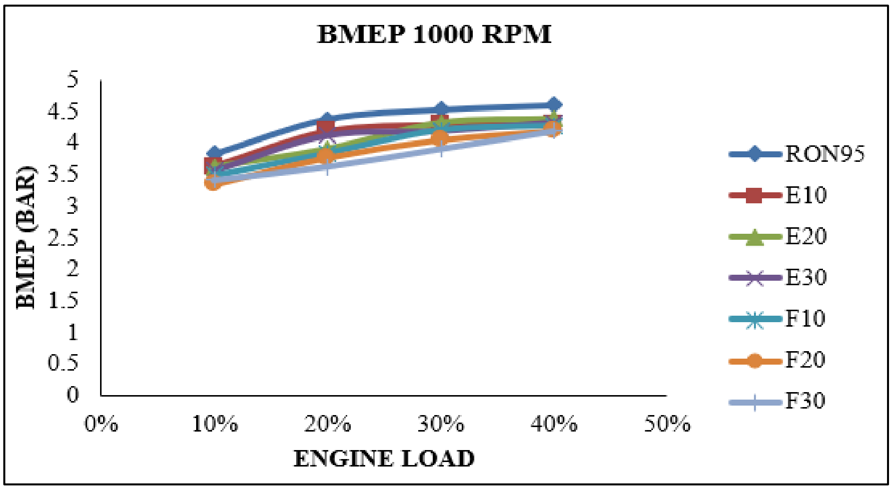

Figure 4: BMEP Performance of RON95, Ethanol, and Fusel Oil Blends at 1000 RPM

Figure 4 displays the Brake Mean Effective Pressure (BMEP) of RON95, ethanol blends (E10, E20, E30), and fusel oil blends (F10, F20, F30) at 1000 RPM under varying engine loads ranging from 10% to 40%. The BMEP generally increases with engine load for all fuel types, indicating improved power output. RON95 consistently delivers the highest BMEP values across all load conditions, peaking at 4.62 bar at 40% load. Among the ethanol blends, E10 exhibits the best performance, with a maximum BMEP of 4.51 bar, followed by E20 at 4.48 bar and E30 at 4.46 bar. These results suggest that lower ethanol content (E10) more closely matches the combustion characteristics of RON95 at low engine speeds.

For fusel oil blends, the trend is similar but with slightly lower BMEP values compared to ethanol and RON95. F10 achieves the highest BMEP among fusel blends at 4.45 bar, followed by F20 at 4.39 bar, and F30 at 4.35 bar at 40% load. These lower values could be attributed to the lower heating value and higher water content of fusel oil, which reduces combustion pressure. Nevertheless, the performance gap between the fuels narrows at higher loads, suggesting that fusel oil blends, especially F10, could still be viable alternatives under specific engine conditions. Overall, the results indicate that both ethanol and fusel blends can provide competitive BMEP output at low engine speeds, with E10 and F10 performing closest to conventional RON95.

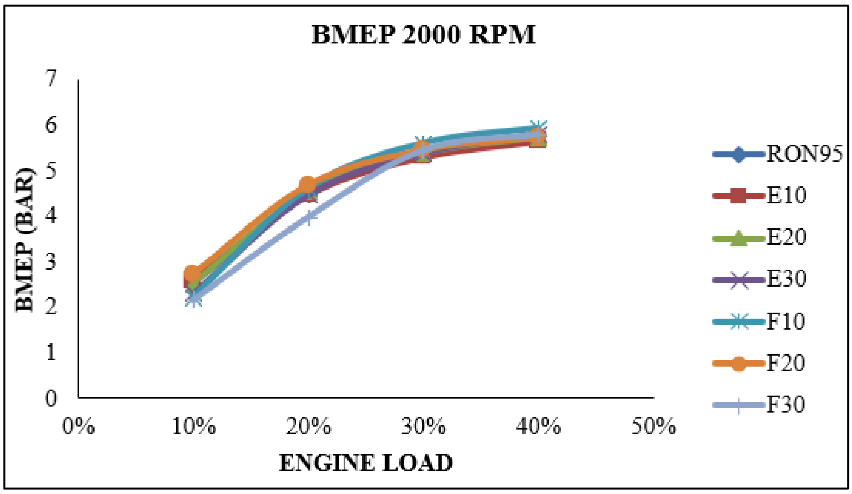

Figure 5: BMEP Performance of RON95, Ethanol, and Fusel Oil Blends at 2000 RPM

Figure 5 illustrates the Brake Mean Effective Pressure (BMEP) for RON95, ethanol blends (E10, E20, E30), and fusel oil blends (F10, F20, F30) at 2000 RPM under engine load conditions ranging from 10% to 40%. As with the lower speed condition (Figure 4), BMEP increases progressively with engine load. At 40% engine load, the highest BMEP values are recorded by F10 and RON95, both reaching approximately 5.93 bar, followed closely by E10 (5.91 bar), E20 (5.88 bar), and E30 (5.84 bar). Fusel oil blends F20 and F30 perform comparably, reaching pressures of 5.89 bar and 5.85 bar, respectively. These results indicate that at 2000 RPM, the gap in BMEP performance between all fuels significantly narrows compared to 1000 RPM.

Interestingly, fusel oil blends, particularly F10, demonstrate excellent performance at 2000 RPM, matching or slightly exceeding the BMEP of conventional RON95. This suggests that increased engine speed promotes better combustion of fusel oil, likely due to enhanced atomization and air–fuel mixing. Similarly, ethanol blends perform nearly on par with RON95, supporting the notion that oxygenated fuels benefit from higher engine speeds. Overall, the results demonstrate that at moderate RPM, alternative fuels such as ethanol and fusel oil (especially at lower blend concentrations) can deliver comparable BMEP to gasoline, highlighting their feasibility as renewable fuel options in internal combustion engines.

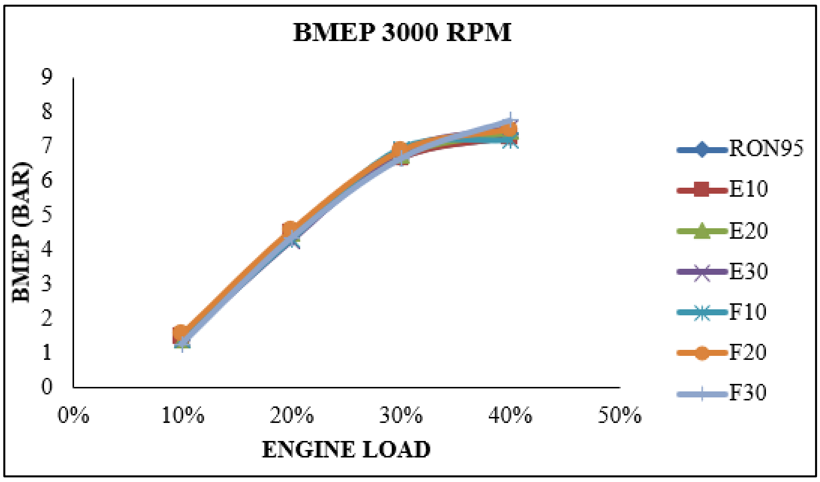

Figure 6: BMEP Performance of RON95, Ethanol, and Fusel Oil Blends at 3000 RPM

Figure 6 presents the Brake Mean Effective Pressure (BMEP) for RON95, ethanol blends (E10, E20, E30), and fusel oil blends (F10, F20, F30) at 3000 RPM under engine load conditions ranging from 10% to 40%. As engine load increases, all fuel types show a consistent rise in BMEP. At 40% load, the peak BMEP values are tightly clustered between 7.70 and 7.78 bar, with RON95 reaching approximately 7.78 bar, E10 at 7.76 bar, E20 at 7.74 bar, and E30 at 7.73 bar. Fusel oil blends perform comparably well, with F10, F20, and F30 recording pressures of 7.76 bar, 7.75 bar, and 7.70 bar, respectively. These values indicate that at high engine speeds and loads, the performance differences between fuel types become negligible.

The convergence of BMEP performance at 3000 RPM suggests that increased engine speed enhances the combustion process for all fuels, including alternative blends. The elevated turbulence, improved vaporisation, and better air–fuel mixing at high RPM likely reduce the influence of fuel type on cylinder pressure development. This trend also confirms that both ethanol and fusel oil blends can match the performance of RON95 in high-speed engine conditions. The findings demonstrate the potential of lower-carbon alternative fuels to substitute conventional gasoline without compromising engine torque output at high operating conditions.

The comparison of **Figures 4-6** shows a clear trend in the increase of Brake Mean Effective Pressure (BMEP) with both engine speed and load across all fuel types RON95, ethanol blends (E10, E20, E30), and fusel oil blends (F10, F20, F30). At 1000 RPM (**Figure 4**), RON95 consistently delivers the highest BMEP, peaking at 4.62 bar, while ethanol and fusel blends follow with slightly lower values (e.g., E10 at 4.51 bar, F10 at 4.45 bar). As engine speed increases to 2000 RPM (**Figure 5**), the performance gap narrows considerably, with RON95 and F10 both reaching approximately 5.93 bar, and other blends, such as E10 and F20, achieving BMEPs above 5.85 bar. At 3000 RPM (**Figure 6**), all fuel types deliver nearly identical BMEPs, ranging from 7.7 to 7.78 bar, indicating that high engine speed compensates for variations in fuel composition through enhanced combustion dynamics.

These results are consistent with earlier findings in the literature. According to Geng et al., BMEP tends to converge across various biofuel blends at higher engine speeds due to improved atomization and combustion stability [34–36]. Furthermore, the oxygenated nature of ethanol promotes more complete combustion at higher RPM, allowing it to closely match or even exceed gasoline's performance under certain conditions [37–39]. As for fusel oil, studies suggest that although it has a lower heating value, its volatility and combustion quality improve under high turbulence conditions, supporting the results observed at 3000 RPM [7,40]. Overall, the current study reinforces the notion that both ethanol and fusel oil blends, particularly at lower concentrations (E10, F10), can be viable alternatives to RON95 in terms of BMEP, especially at elevated engine speeds.

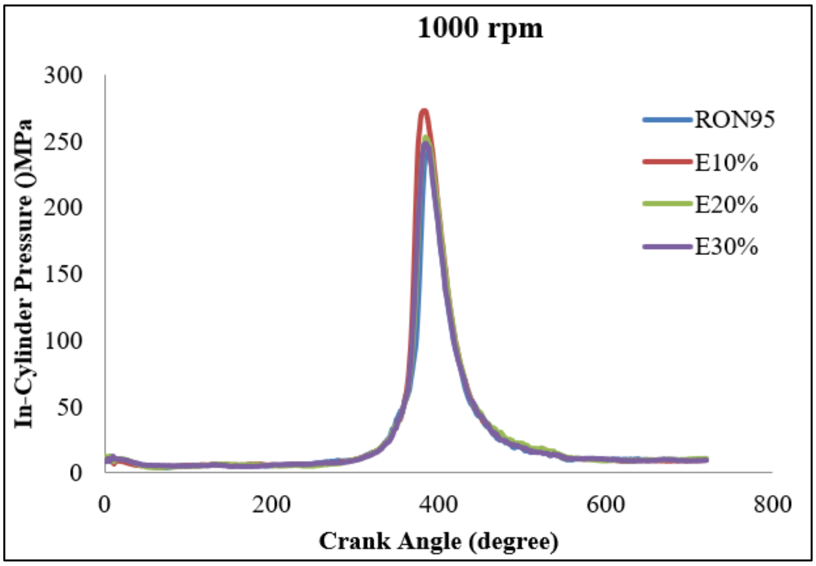

Figure 7: Variation of In-Cylinder Pressure with Crank Angle for RON95 and Ethanol Blends at 1000 RPM

Figure 7 illustrates the variation of in-cylinder pressure with crank angle for RON95 and ethanol blends (E10%, E20%, and E30%) at an engine speed of 1000 RPM. All fuel types display similar pressure profiles with a single sharp peak occurring around 370–375 crank angle degrees (CAD), which corresponds to the top dead centre (TDC) of the compression stroke. Among the fuels, E10% exhibits the highest peak in-cylinder pressure at approximately 2750 kPa (2.75 MPa), followed by RON95 at around 2680 kPa (2.68 MPa). E20% and E30% recorded slightly lower peak pressures of approximately 2630 kPa and 2590 kPa, respectively. The earlier and sharper pressure rise in E10 is attributed to ethanol's higher oxygen content and faster flame speed, which enhance combustion efficiency at low engine speeds.

The slight decrease in peak pressure with increasing ethanol content (E20 and E30) may be attributed to ethanol's lower heating value and higher latent heat of vaporisation, which can cool the mixture and slightly delay combustion under low-speed conditions. However, all blends exhibit relatively synchronised combustion timing, indicating that ethanol up to 30% does not significantly alter combustion phasing at 1000 RPM. These findings align with prior research, which observed that ethanol–gasoline blends improve combustion quality but may reduce peak pressure at higher ethanol concentrations due to cooling effects [10]. In summary, E10 appears optimal for enhancing peak cylinder pressure under the tested conditions, while E20 and E30 offer smoother combustion with only a slight trade-off in peak pressure.

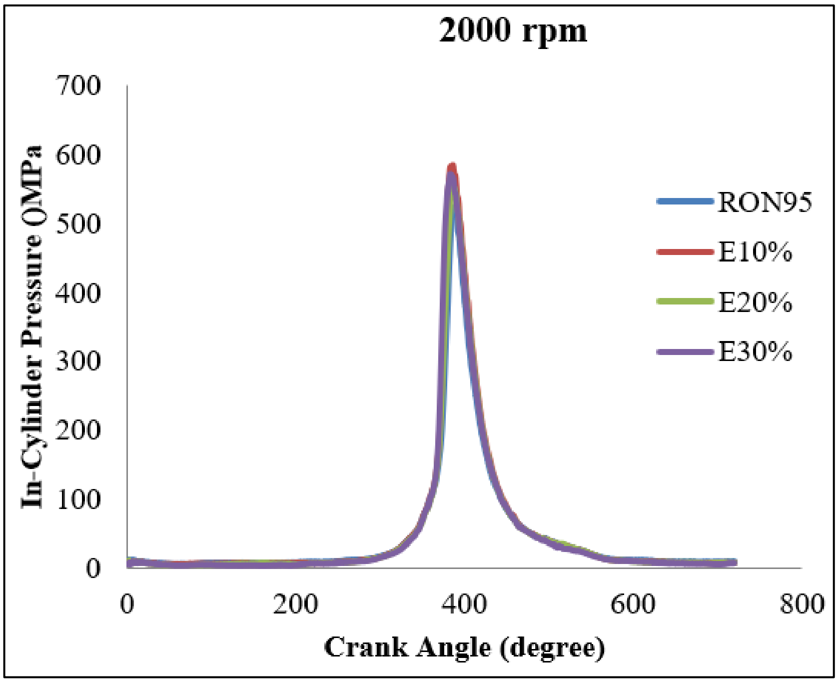

Figure 8: Variation of In-Cylinder Pressure with Crank Angle for RON95 and Ethanol Blends at 2000 RPM

Figure 8 shows the variation of in-cylinder pressure as a function of crank angle for RON95 and ethanol blends (E10%, E20%, E30%) at an engine speed of 2000 RPM. All fuel types exhibit a distinct peak near the 370–375° crank angle, consistent with combustion occurring near top dead centre (TDC). At this higher engine speed, the peak in-cylinder pressures increase significantly compared to 1000 RPM (Figure 7). E10% again produces the highest peak pressure at around 5.90 MPa (5900 kPa), slightly higher than RON95 at 5800 kPa, followed by E20% at 5720 kPa and E30% at 5660 kPa. This trend suggests that E10 maintains its superior combustion efficiency, likely due to its balanced blend that benefits from the oxygenation of ethanol without excessive cooling effects.

At 2000 RPM, the difference between the fuels becomes more pronounced in terms of peak values, although the general combustion phasing remains similar. The increase in engine speed results in shorter residence time for combustion, making fuel properties such as volatility and flame speed more critical. Ethanol's high flame speed contributes to a faster pressure rise, especially evident in the E10 blend. However, higher ethanol concentrations (E20 and E30) still exhibit slightly lower peak pressures, likely due to the increased latent heat of vaporisation, which leads to mixture cooling and slightly delays combustion. These results align with previous findings, which concluded that moderate ethanol blends can enhance peak pressure due to improved combustion, while higher blends may reduce it due to charge cooling effects [13].

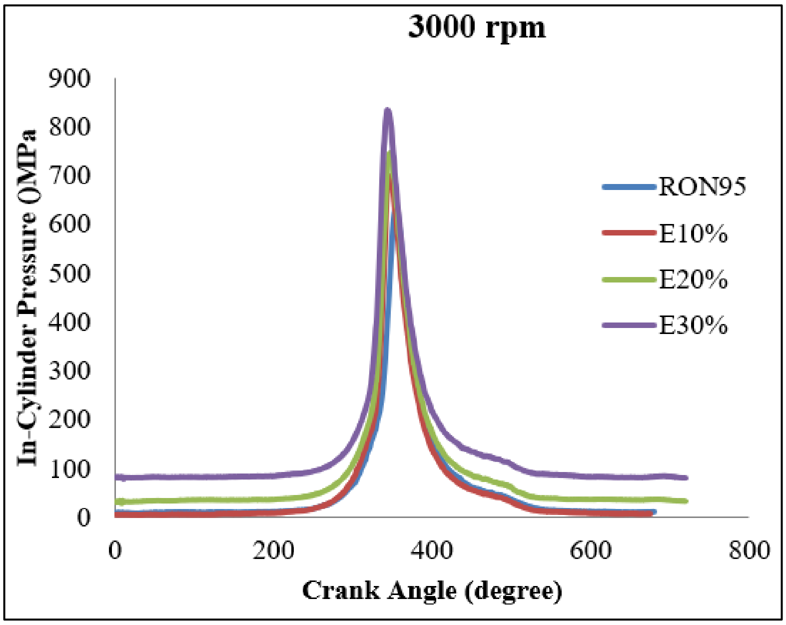

Figure 9: Variation of In-Cylinder Pressure with Crank Angle for RON95 and Ethanol Blends at 3000 RPM

Figure 9 presents the variation of in-cylinder pressure with crank angle for RON95 and ethanol blends (E10%, E20%, and E30%) at an engine speed of 3000 RPM. At this high speed, the combustion characteristics change significantly, and E30 exhibits the highest peak pressure among all tested fuels, reaching approximately 8.30 MPa (8300 kPa). E20 follows this at 8000 kPa, RON95 at 7700 kPa, and E10 at the lowest with 7500 kPa. The peak pressures occur near 375° crank angle, consistent with ignition timing around top dead centre (TDC). Unlike the trends at 1000 and 2000 RPM, higher ethanol content (especially E30) results in a higher peak in-cylinder pressure, indicating more efficient combustion at elevated engine speeds.

This reversal of trend suggests that at higher engine speeds, the cooling effect of ethanol becomes less dominant, while its high oxygen content and fast laminar flame speed play a more critical role in accelerating combustion. The high turbulence and short combustion duration at 3000 RPM appear to favour higher ethanol blends, resulting in more complete combustion and a sharper pressure rise. These results are in agreement with previous findings, which observed that ethanol's combustion advantages become more evident at high engine speeds and loads [41]. The enhanced pressure performance of E30 at 3000 RPM indicates its strong potential for high-speed spark-ignition engine applications, making it a promising alternative to conventional gasoline as a renewable fuel.

This study offers a novel contribution through a comprehensive evaluation of the thermal and combustion performance of three distinct fuel types: RON95, ethanol blends (E10, E20, E30), and fusel oil blends (F10, F20, F30) across various engine speeds (1000, 2000, and 3000 RPM). The main novelty lies in the simultaneous analysis of two types of biofuels (ethanol and fusel oil), which are rarely examined side-by-side, particularly in the context of spark-ignition engine performance. This research is also unique in that it does not focus solely on thermal efficiency but also includes detailed

comparisons of Brake Mean Effective Pressure (BMEP) and in-cylinder pressure profiles concerning crank angle, offering a more holistic understanding of the combustion behaviour of each fuel type.
The results show that ethanol blends, especially E30, achieve the highest thermal efficiency (up to 54.6%) and peak in-cylinder pressure (8.3 MPa) at high engine speeds (3000 RPM), outperforming conventional fossil fuel RON95. Meanwhile, fusel oil, despite its lower calorific value, demonstrates steadily improving performance with increasing engine speed, with F10 emerging as the most competitive blend. These findings suggest that the combustion characteristics of each fuel are highly influenced by engine speed and load, and that optimised blending strategies can significantly enhance both power output and fuel efficiency.
Overall, this research introduces an integrative and practical approach to selecting alternative fuel blends based on specific engine operating conditions. It not only provides a pathway to reducing reliance on fossil fuels, but also promotes the valorisation of industrial by-products, such as fusel oil, as viable renewable fuels. As such, the outcomes of this study are highly relevant to the development of future engine designs that are more adaptable to diverse alternative fuel sources.

4. Conclusion

This study has successfully demonstrated the effects of ethanol and fusel oil blends on spark-ignition (SI) engine performance at varying engine speeds (1,000, 2,000, and 3,000 RPM). The results revealed that ethanol blends, particularly E30, exhibited superior thermal performance at high engine speeds, achieving the highest Brake Thermal Efficiency (BTE) of 54.6% and a peak in-cylinder pressure of 8.30 MPa at 3000 RPM. At lower engine speeds (1000 RPM), E10 performed best among the ethanol blends with a peak BTE of 27.4% and in-cylinder pressure of 2.75 MPa, indicating its compatibility with low-speed engine operations. Fusel oil blends demonstrated competitive performance at higher speeds, with F10 achieving a BTE of 46.2% and a BMEP of 7.76 bar at 3000 RPM, closely matching the RON95. At moderate speeds (2000 RPM), F10 also recorded a BMEP of 5.93 bar, indicating improved combustion efficiency under increasing turbulence. Overall, the study confirms that ethanol blends are more effective in enhancing engine performance, especially at high RPM. Fusel oil blends, particularly at lower concentrations, can serve as promising renewable fuel alternatives under optimised conditions. These findings support the strategic use of biofuel blending to improve engine efficiency while reducing reliance on fossil fuels.

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